CHAPTER 12
GAS TURBINE COMBUSTORS

The heat is added to the air flowing through the gas turbine in the combustors.[1] The air leaving the compressor enters the combustors. Its temperature increases while the pressure drops slightly across the combustors. Thus, combustors are direct-fired air heaters. The fuel is burned almost stoichiometrically with 25 to 35 percent of the air entering the combustors. The combustion products mix with the remaining air to arrive at a suitable temperature for the turbine. The three major types of combustors are tubular, tuboannular, and annular. All combustors, despite their design differences, have the following three zones:

1. Recirculation zone
2. Burning zone
3. Dilution zone

The fuel is evaporated and partially burned in the *recirculation zone.* The remainder of the fuel is burned completely in the *burning zone.* The dilution air is mixed with the hot gas in the *dilution zone.* If the combustion is not complete at the end of the burning zone, the addition of dilution air can chill the hot gas. This prevents complete combustion of the fuel. However, there is evidence that some combustion occurs in the dilution zone if the burning zone is run overrich.

The fuel-to-air ratio varies during transient conditions. It is high during the acceleration phase and low during the deceleration phase. Thus, the combustor should be able to operate over a wide range of mixtures. The combustor performance is measured by efficiency, pressure drop across the combustor, and evenness of the outlet temperature profile.

The combustor efficiency is a measure of combustion completeness. It affects the fuel consumption directly because the unburned fuel is wasted. The combustor efficiency is the ratio of the increase in gas enthalpy and the theoretical heat input of the fuel. It is given by

$$\eta_c = \frac{\Delta h_{\text{actual}}}{\Delta h_{\text{theoretical}}} = \frac{(\dot{m}_a + \dot{m}_f)\, h_3 - \dot{m}_a h_2}{\dot{m}_f(\text{LHV})}$$

where η_c = combustor efficiency
$\dot{m}_a$ = mass flow of gas
$\dot{m}_f$ = mass flow of fuel
h_3 = enthalpy of gas leaving the combustor
h_2 = enthalpy of gas entering the combustor
LHV = fuel heating value

The pressure drop across the combustor affects the fuel consumption and power output. It is normally around 2 to 8 percent of the static pressure. This pressure drop is equivalent to a decrease in compressor efficiency. It results in an increase in the fuel consumption and a lower power output from the machine.

The combustor outlet temperature profile must be uniform. Any nonuniformity in this temperature profile causes thermal stress on the turbine blades, which could lead to fracture.

It also results in a decrease of the efficiency and power output of the machine. Satisfactory operation of the combustor is achieved by having a self-sustaining flame and stable combustion over a wide range of fuel-to-air ratio to prevent loss of ignition during transient operation.

The temperature gradients, carbon deposits, and smoke should be minimized due to the following reasons:

- Temperature gradients cause warps and cracks in the liner.
- Carbon deposits increase the pressure loss and distort the flow patterns.
- Smoke is environmentally objectionable.

During the last half-century, the operating conditions of gas turbine combustors have changed significantly. Following is a summary of these changes:

- Combustion pressures have increased from 5 to 50 atmosphere (atm) (73.5 to 735 psi).
- Inlet air temperatures have increased from 572 to 1472°F (300 to 800°C).
- Combustor outlet temperatures have increased from 1620 to 3092°F (900 to 1700°C).

Despite these major changes in operating conditions, today's combustors operate at almost 100 percent combustion efficiency over their normal operating range and during idling conditions. They also provide a substantial reduction in pollutant emissions. In addition, the life expectancy of aeroderivative (aero) engine liners has increased from a few hundred hours to many tens of thousands of hours. Although many problems have been overcome, improvements are still required in the following areas:

- To further reduce pollutant emissions, ideas and technology are still needed.
- To accommodate the growing requirements of many industrial engines having multifuel capability.
- To deal with the problem of acoustic resonance. This problem occurs when combustion instabilities become coupled with combustor acoustics.

COMBUSTION TERMS

The following is a list of definitions of some of the terms used with combustors:

Reference velocity. The theoretical flow velocity of air through an area equal to the maximum cross section of the combustor casing. It is around 80 to 135 ft/s (24.5 to 41 m/s) in a straight-through-flow turbojet combustor.

Profile factor. This is the ratio of the maximum exit temperature and the average exit temperature.

Traverse number (temperature factor). (1) The maximum gas temperature minus the average gas temperature divided by the average temperature increase in a nozzle design. (2) The difference between the maximum and the average radial temperature. The traverse number should be between 0.05 and 0.15.

Stoichiometric proportions. The proportions of the reactants (fuel and oxygen) are such that there is exactly enough oxygen to complete the reaction (combustion of the fuel).

Equivalence ratio. The ratio of oxygen content at stoichiometric conditions and actual conditions:

$$\phi = \frac{\text{(Oxygen/fuel at stoichiometric conditions)}}{\text{(Oxygen/fuel at actual conditions)}}$$

Pressure drop. The pressure drop across the combustor is around 2 to 10 percent of the compressor outlet pressure. It reduces the efficiency of the unit by the same percentage.

COMBUSTION

Combustion is a chemical reaction between the fuel (carbon or hydrogen) and oxygen. Heat is released during this reaction. The combustion products are carbon dioxide and water. The combustion of natural gas is given by

$$\underset{\text{(methane + oxygen)}}{CH_4 + 4O} \rightarrow \underset{\text{(carbon dioxide + water + heat)}}{CO_2 + 2H_2O + \text{heat}}$$

Since the chemical composition of air is 21 percent oxygen and 79 percent nitrogen, there are four molecules of nitrogen for every molecule of oxygen in air. Thus, the complete combustion reaction of methane can be written as follows:

$$\underset{\text{(methane + air)}}{1CH_4 + 2(O_2 + 4N_2)} \rightarrow \underset{\text{(carbon dioxide + nitrogen + water + heat)}}{1CO_2 + 8N_2 + 2H_2O + \text{heat}}$$

Therefore, the combustion of 1 m^3 of methane requires 2 m^3 of oxygen and 8 m^3 of nitrogen. During the combustion of methane, another chemical reaction occurs, leading to the formation of nitric acid. It is written as follows:

$$2N + 5O + H_2O \rightarrow \underset{\substack{\text{nitric}\\\text{oxide}}}{2NO} + 3O + H_2O \rightarrow \underset{\substack{\text{nitric}\\\text{acid}}}{2HNO}$$

This reaction indicates that the formation of nitric acid can be reduced by controlling the formation of nitric oxide. Reducing the combustion temperature can achieve this goal. The combustion temperature is normally around 3400 to 3500°F (1870 to 1927°C). The volumetric concentration of nitric oxide in the combustion gas at this temperature is around 0.01 percent. This concentration will be substantially reduced if the combustion temperature is lowered. A reduction in the combustion temperature to 2800°F (1538°C) at the burner will reduce the volumetric concentration of nitric oxide to below 20 parts per million (ppm) (0.002 percent). This level is reached in some combustors by injecting a noncombustible gas (flue gas) around the burner to cool the combustion zone.

If the fuel contains sulfur (e.g., liquid fuels), sulfuric acid will be a by-product of the combustion. Its reaction can be written as follows:

$$H_2S + 4O \rightarrow \underset{\substack{\text{sulfuric}\\\text{oxide}}}{SO_3} + H_2O \rightarrow \underset{\substack{\text{sulfuric}\\\text{acid}}}{H_2SO_4}$$

The amount of sulfuric acid cannot be reduced during combustion. The formation of sulfuric acid can be eliminated by removing the sulfur from the fuel. There are two different sweetening processes to remove the sulfur from the fuel that will be burned.

As mentioned earlier, the ideal volumetric ratio of air to methane is 10:1. If the actual volumetric ratio is lower than 10:1, the combustion products will contain carbon monoxide. This reaction can be written as follows:

$$1CH_4 + 11/2\ (O_2 + 4N_2) \rightarrow 2H_2O + 1CO + 6N_2 + \text{heat}$$

The volumetric ratio of air to methane in gas turbines is maintained normally above 10:1. Thus, carbon monoxide is not a problem.

COMBUSTION CHAMBER DESIGN

The simplest combustor consists of a straight-walled duct connecting the compressor and turbine. This combustor is impractical due to the excessive pressure drop across it. The pressure drop from combustion is proportional to the square of the air velocity. Since the compressor air discharge velocity is around 558 ft/s (170 m/s), the pressure drop will be around one-third of the pressure increase developed by the compressor. This pressure loss can be reduced to an acceptable value by installing a diffuser. Even with a diffuser, the air velocity is still high to permit stable combustion. A low-velocity region is required to anchor the flame. This is accomplished by installing a baffle (Fig. 12.1). An eddy region forms behind the baffle. It draws the gases in to be burned completely. This steady circulation of the flow stabilizes the flame and provides continuous ignition.

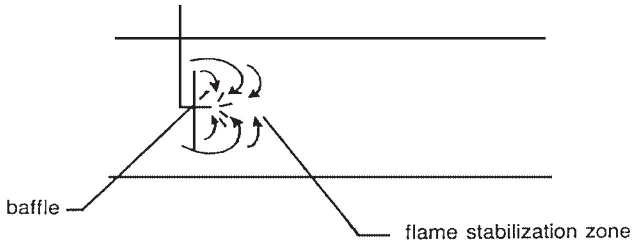

FIGURE 12.1 Baffle added to straight-walled duct to create a flame stabilization zone.

Other methods are used to stabilize the flame in the primary zone. Figures 12.2 and 12.3 illustrate two such designs. A strong vortex is created by swirl vanes around the fuel nozzle in the first design. The second design relies on formation of another flow pattern by admitting combustor air through rings of radial jets. The jet impingement at the combustor axis results in the formation of a torroidal recirculation zone that stabilizes the flame.

The air velocity has a significant effect on the stabilization of the flame. Figure 12.4 is a general stability diagram. It illustrates the decrease in the range of burnable mixtures as velocity increases. The size of the baffle also affects the limits of burnable mixtures and the pressure drop across the combustor. The flow velocity in the combustor is maintained well

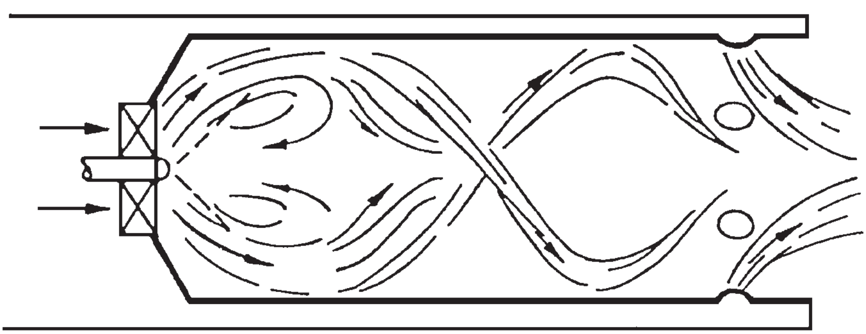

FIGURE 12.2 Flame stabilization region created by swirl vanes.

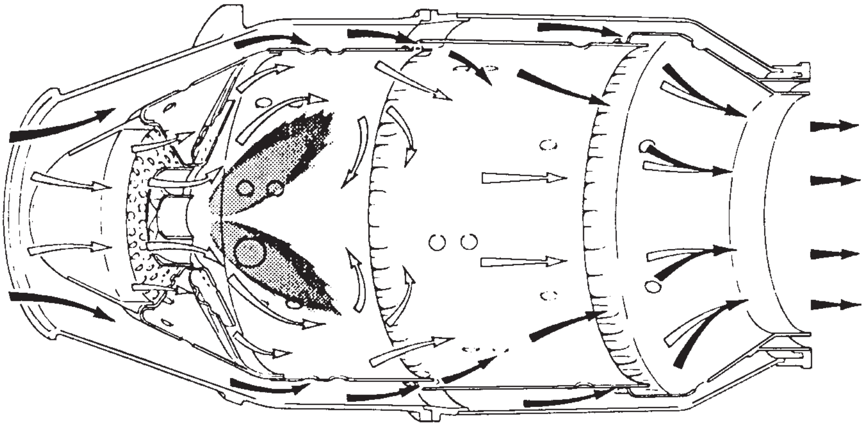

FIGURE 12.3 Flame stabilization created by impinging jets and general airflow pattern. (© *Rolls-Royce Limited.*)

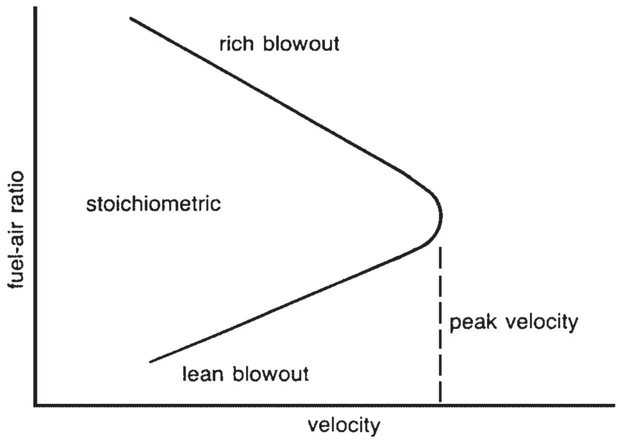

FIGURE 12.4 Range of burnable fuel-to-air ratios versus combustor gas velocity.

below the blowout limit to accommodate a wide operating range of fuel-to-air ratios. The air velocity does not normally vary with the load, because the compressor operates at a constant speed. In some applications, the mass flow varies with the load. In these applications, the static pressure varies in a similar fashion to the load. Thus, the volumetric flow rate remains almost constant.

The fuel-to-air ratio is around 1:60 in the primary zone of the combustor. The remaining air (known as *secondary,* or *dilution, air*) is added when the primary reaction is completed. The dilution air should be added gradually to prevent quenching of the reaction. This is accomplished by adding a flame tube (Fig. 12.5). The flame tubes are designed to produce a desirable outlet temperature profile. Their adequate life in the combustor environment is assured by film cooling of the liner.

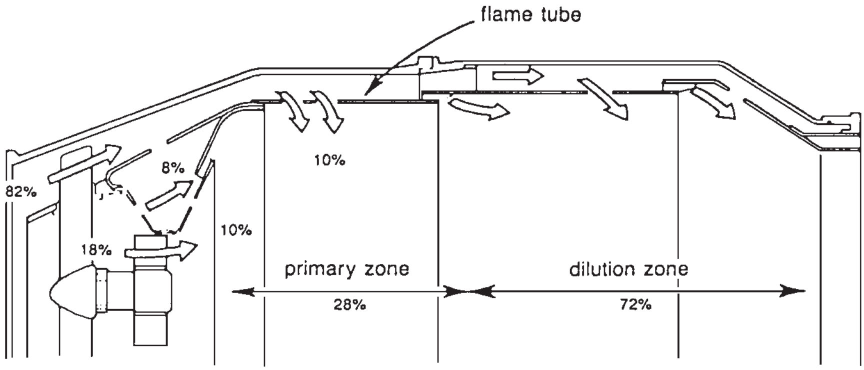

FIGURE 12.5 Addition of a flame tube distributes flow between the primary and dilution zones.

The air flowing in the annulus between the liner and the casing enters the space inside the liner through holes and slots. This air provides film cooling of the liner. The holes and slots are designed to divide the liner into distinct zones for flame stabilization, combustion, and dilution.

Flame Stabilization

Swirl vanes around the fuel nozzle generate a strong vortex flow in the combustion air within the combustor (Fig. 12.6). The flame is recirculated toward the fuel nozzle due to the creation of a low-pressure region at the combustor axis. Air flows to the center of the vortex through radial holes around the liner. This allows the flame to grow to some extent. The jet impingement along the combustor axis generates upstream flow, which forms a torroidal recirculation zone that stabilizes the flame.

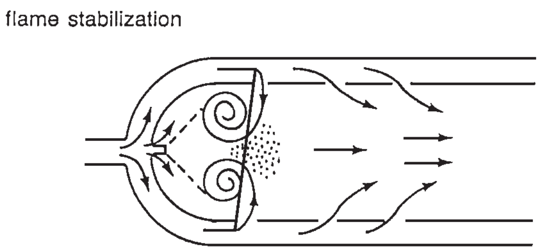

FIGURE 12.6 Flow pattern by swirl vanes and radial jets.

Combustion and Dilution

Combustors will not generate smoke when the equivalence ratio in the primary zone is below 1.5. Visible smoke is considered an air pollution problem. Following combustion, the rich burning mixture leaves the combustion zone and mixes with the air jets entering the liner, resulting in intensive turbulence throughout the combustor. Dilution air enters through holes in the liner and mixes with the combustion products to lower the temperature of the products. The mixture enters the turbine at a suitable temperature for the blade materials.

Film Cooling of the Liner

The liner is exposed to the highest temperature in the gas turbine due to combustion and heat radiated by the flame. The life of the liner is extended by using material having a high resistance to thermal stress and fatigue and by cooling the liner using an air film. This cooling is accomplished by admitting air through rows of small holes in the liner.

Fuel Atomization and Ignition

The liquid fuel used in gas turbines should be atomized in the form of a fine spray when it is injected into the combustors. Figure 12.7 illustrates a typical low-pressure fuel atomization nozzle.

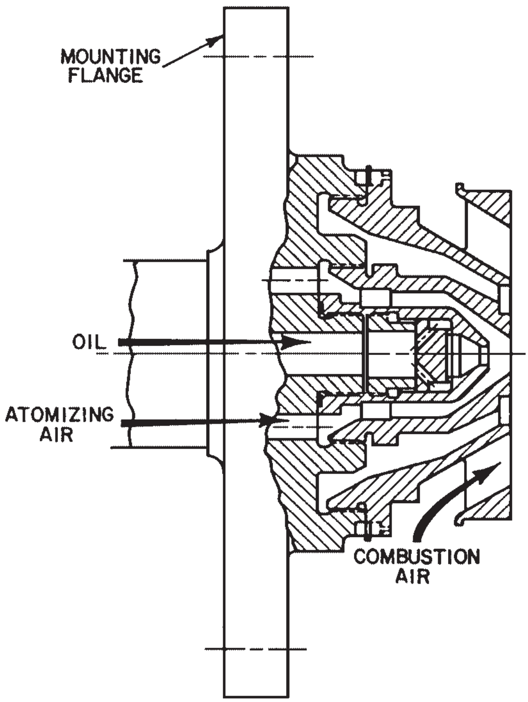

FIGURE 12.7 Air atomized liquid fuel nozzle. (*Courtesy of General Electric Company.*)

The flow rate in a pressure-atomizing fuel nozzle varies with the square root of the pressure. Some gas turbines require atomizers having a wide capacity range. This is accomplished using a *dual-orifice atomizer,* which has two swirl chambers. The first, known as the *pilot,* has a small orifice. The second is the *main swirl chamber.* It has a much larger orifice. When the flow is low, the fuel is supplied through the pilot orifice. This ensures good-quality atomization. When the flow increases, the fuel pressure increases as well. A valve opens at a predetermined pressure. The flow is now diverted through the main atomizer. This arrangement provides satisfactory atomization over a wide range of flows.

Interconnecting tubes connect all of the combustors together. When ignition is established in one combustor, the flame spreads to the remaining combustors immediately. Igniters are only installed in a few combustors. Figure 12.8 illustrates an igniter plug. It is a surface discharge plug. Thus, the energy does not jump over an air gap. A semiconductive material covers the end of the plug. It permits an electrical leakage to the body from the central high-tension electrode. This discharge provides a high-intensity flash from the electrode to the body.

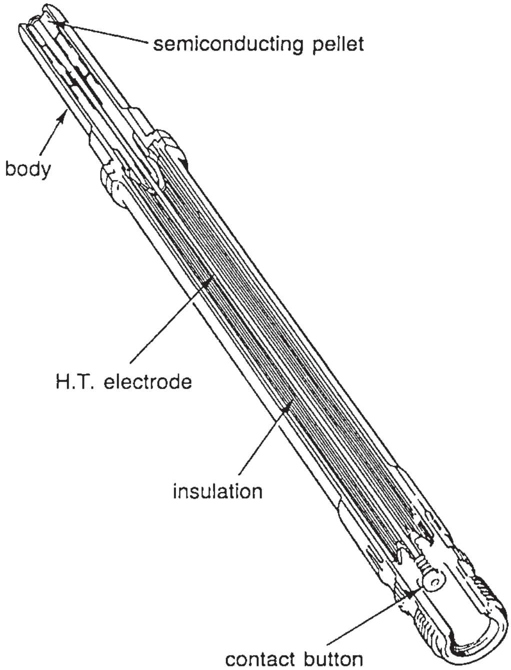

FIGURE 12.8 An igniter plug. (© *Rolls-Royce Limited.*)

Gas Injection

Few problems occur during combustion of gaseous fuels having a high heat content [British thermal unit (Btu)], such as natural gas. However, gaseous fuels having a low heat content may cause problems. The fuel flow rate could reach 20 percent of the total combustor mass flow. This will generate a significant mismatch between the flow in the compressor and the flow in the turbine. This problem will be more significant if the gas turbine was intended for a multifuel application. Low-heat-content gases also have a low burning rate. This may require larger combustors. An additional increase in the size of the combustors is needed to accommodate the large volumetric flow of fuel. Difficulties can also occur in achieving the correct mixing rate in the combustors. The gaseous fuel is normally injected through orifices, swirlers, or venturi nozzles.

Wall Cooling

The liner contains the combustion products. It also facilitates distribution of the correct amount of air to the various zones inside the combustor. The liner must have the mechanical

strength to withstand the buckling force created by a difference in pressure across its wall. It must also be able to withstand the cyclical thermal stresses. These requirements are accomplished by the following:

- Making the liner of a high-temperature, oxidant-resistant material.
- Using the cooling air effectively. Most modern combustors use up to 40 percent of the total airflow for cooling the liner wall.

The temperature of the liner wall is determined by the following heat balance:

- Heat received by radiation and convection from the combustion of hot gases
- Heat removed from the liner by convection to the surrounding air and by radiation to the casing

It has become increasingly difficult to provide effective cooling for the liner wall. This stems from the increase in temperature of the inlet air entering the combustors. During the last 60 years, the pressure ratio in gas turbines has increased from 7 to 45, and the firing temperature has increased from 1500°F (815°C) to 2600°F (1427°C). This increase in temperature is mainly caused by an increase in compressor discharge pressure. There is a corresponding increase in temperature at the discharge of the compressor as a result of the increased pressure. The temperature in modern combustors is reaching higher values to increase the thermal efficiency in the gas turbine.

Wall Cooling Techniques

A louver cooling technique was used on many early gas turbines. The combustors were made in the form of cylindrical shells. They had a series of annular passages at the intersection points of the shells. A film of cooling air was injected through these passages along the hot side of the liner wall. It provided a thermal barrier from the hot gases. Simple wigglestrip louvers were used to control the heights of the annular gaps. This technique had major problems with controlling airflow.

Splash cooling devices were also used. They did not provide any problems with flow control. In this system, a row of small-diameter holes was drilled through the liner. The air entered the liner through the holes. A skirt acted as an impingement baffle for the flow. It deflected the cooling airflow along the liner wall. Both techniques (i.e., wigglestrip louvers and splash cooling) were used until annular combustors were introduced.

Angled-effusion cooling (AEC) is used on some modern combustors. Different patterns of small holes are drilled through the liner wall at a shallow angle to the surface. The cooling air enters the liner through the holes. It removes the heat from the liner and also provides a thermal barrier to the wall. This technique is among the best used in modern gas turbines. Combustors of the GE-90 use this technique. It reduced the air cooling requirement by 30 percent. Its main disadvantage is an increase in the weight of the liner by around 20 percent. This is mainly caused by the need for an increased thickness in the wall to meet the buckling stress.

Some large industrial gas turbines use refractory brick to shield the liner wall from heat. This technique is used on these engines because their size and weight are of minimal importance. However, most industrial and aero engines cannot use this technique due to the significant increase in weight. Some engines use metallic tiles for this application. For example, the Pratt & Whitney PW-4000 and the V-2500 use metallic tiles in their combustors. The tiles are capable of handling the thermal stresses. The liner handles the mechanical stresses. The tiles are usually cast from alloy materials used for the turbine blades. This material has a much higher temperature rating, at least 100°C higher than typical alloys

used for combustor liners. Also, the liner can be made of relatively inexpensive alloys because it remains at a uniform low temperature. The main disadvantage of using tiles is the significant increase in weight.

Spraying a protective coating on the inner wall of the liner enhances the liner cooling. This coating acts as a thermal barrier. It can reduce the temperature of the liner wall by up to 100°C. These coatings are used on most modern combustors. The materials used for existing combustor liners are nickel- or cobalt-based alloys, such as Niminic 263 or Mastelloy X. Research is underway to develop new liner materials that can withstand the increasing requirements of modern combustors. Possibilities for future combustor material include carbon composites, ceramics, and alloys of high-temperature materials such as columbium. None of these materials are at the stage of development that would permit industrial application.

COMBUSTOR DESIGN CONSIDERATIONS

Cross-sectional area. The combustor cross section is obtained by dividing the volumetric flow by a reference velocity that has been selected for a particular turbine based on a proven performance in a similar unit.

Length. The combustor should have adequate length to provide flame stabilization, combustion, and mixing with dilution air. The length-to-diameter ratio for a typical liner is between 3 and 6. The length-to-diameter ratio for a casing is between 2 and 4.

Combustor material. The material selected for combustors normally has a high fatigue resistance (e.g., Nimonic 75, Nimonic 80, and Nimonic 90). Nimonic 75 is an alloy with 80 percent nickel and 20 percent chromium. Its stiffness is increased by adding a small amount of titanium carbide. It has excellent oxidation and corrosion resistance at high temperatures, adequate creep strength, and good fatigue resistance. It is also easy to press, draw, and mold.

AIR POLLUTION PROBLEMS

Smoke

Smoke is generated normally in fuel-rich combustors. It is normally eliminated by having a leaner primary zone. It is also eliminated by supplying a quantity of air to overrich zones inside the combustors.

Hydrocarbon and Carbon Monoxide

Incomplete combustion generates hydrocarbon (HC) and carbon monoxide (CO). This occurs normally during idle conditions. The idling efficiency of modern units has been improved by providing better atomization and higher local temperatures to eliminate HC and CO.

Oxides of Nitrogen

Combustion produces the main oxide of nitrogen NO (90 percent) and NO_2 (10 percent). These products are pollutants due to their poisonous characteristics, especially at full load. The concentration of nitrogen oxides increases with the firing temperature.

The concentration of nitrogen oxides can be reduced by one of the following three methods:

1. Minimizing the peak flame temperature by operating with a very lean primary zone
2. Injecting water or steam into the combustors to lower the firing temperature
3. Injecting an inert gas into the combustors to lower the firing temperature

The injection of steam or water into the combustors has proven to be an effective method in reducing NO_X emissions by 85 percent (from 300 to 25 ppm).

TYPICAL COMBUSTOR ARRANGEMENTS

The three major categories of combustors are

1. Tubular (single can)
2. Tuboannular
3. Annular

Most of the gas turbines manufactured in Europe use tubular or single-can combustors. These combustors have a simple design and a long life. They can be up to 10 ft (3 m) in diameter and 40 ft (12 m) high. These combustors use special tiles as liners. Damaged tiles can easily be replaced. Tubular combustors can be *straight-through* or *reverse-flow* designs. The air enters these combustors through the annulus between the combustor can and the hot gas pipe, as shown in Fig. 12.9. The air then flows between the liner and the hot

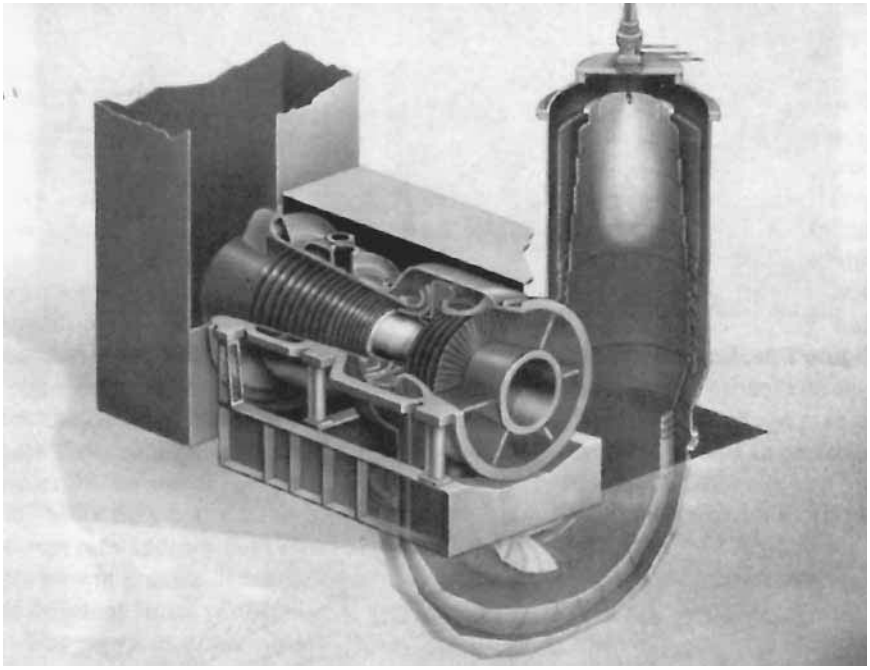

FIGURE 12.9 Single-can combustor. (*Courtesy of Brown Boveri Turbomachinery, Inc.*)

gas pipe and enters the combustion region through the various holes shown. Only 10 percent of the air enters the combustion zone. Around 30 to 40 percent of the air is used for cooling. The rest of the air is used for dilution purposes. Combustors having reverse-flow designs are much shorter than the ones having straight-through designs. These large combustors normally have a ring of nozzles placed in the primary zone area.

Tuboannular combustors are the most popular type of combustors used in gas turbines. Figure 12.10 illustrates the tuboannular or can-annular type of combustors. These combustors are easy to maintain. Their temperature distribution is better than side single-can combustors. They can be a straight-through or reverse-flow design. Most industrial gas turbines use the reverse-flow type.

Figure 12.11 illustrates the straight-through tuboannular combustors. These combustors are used in most aircraft engines. They require a much smaller frontal area than the reverse-flow-type tuboannular combustor. However, they require more cooling air than a single or annular combustor due to their large surface area. The amount of cooling air required can easily be provided in gas turbines using high-heat-content (high-Btu) gas. However, gas turbines using low-Btu gas require up to 35 percent of the total air in the primary zone. Thus, the amount of cooling air will be reduced.

Single-can and annular combustors are more attractive at higher firing temperatures due to their relatively smaller surface area. However, the tuboannular combustors have a more even flow distribution.

Figure 12.12 illustrates an annular combustor. This type of combustor is normally used in aircraft gas turbines. These combustors are usually of the straight-through design. The compressor casing radius is the same as the combustor casing. These combustors require less cooling air than the tuboannular combustors. Thus, they are growing in popularity in high-temperature applications. However, the maintenance of annular combustors is relatively more difficult, and their temperature and flow profiles are less favorable than tuboannular combustors. Annular combustors will become more popular in applications having higher firing temperatures and low-Btu gases.

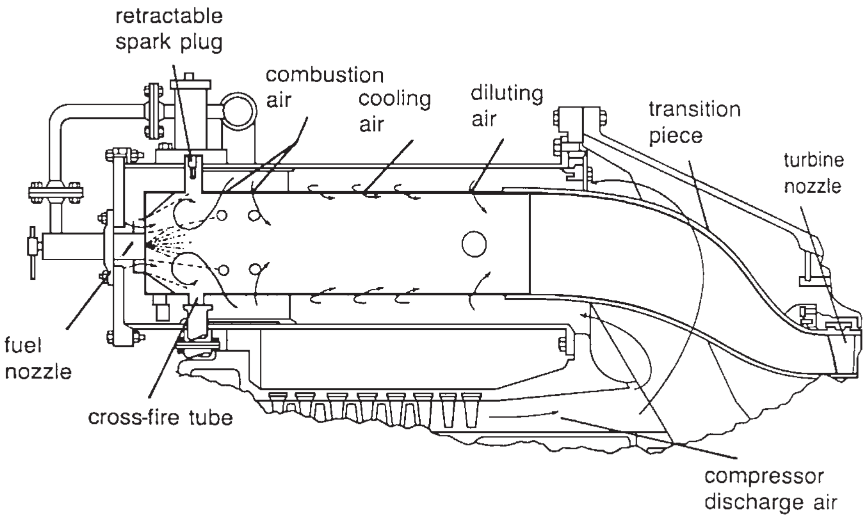

FIGURE 12.10 Can-annular, reverse-flow combustor for a heavy-duty gas turbine. (*Courtesy of General Electric Company.*)

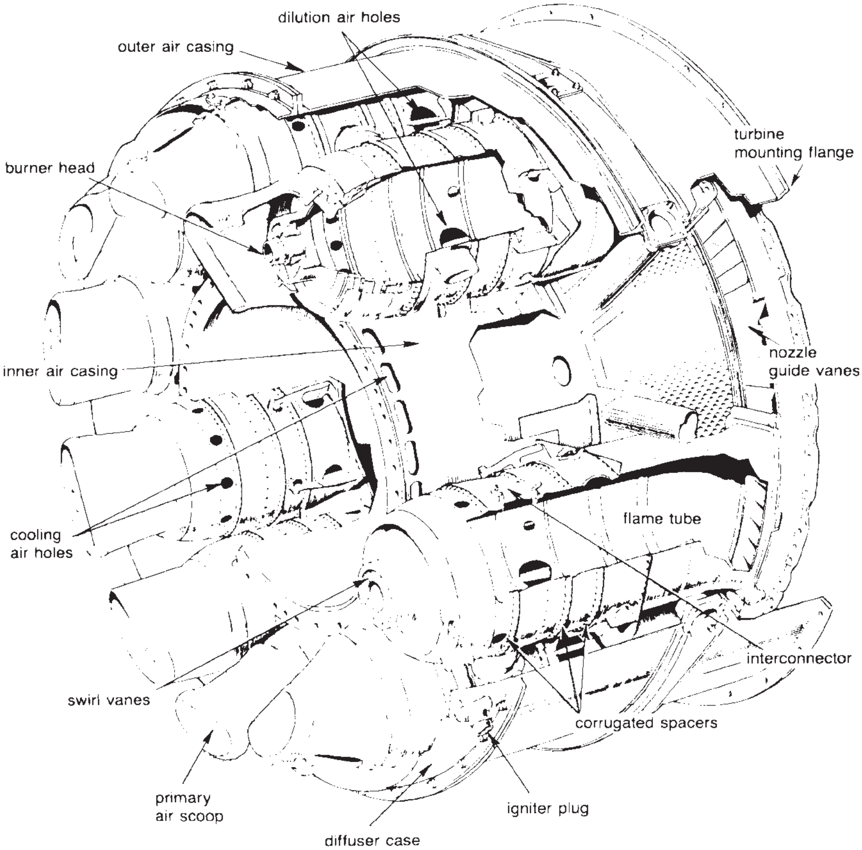

FIGURE 12.11 Straight-through flow-type can-annular combustors. (© *Rolls-Royce Limited.*)

COMBUSTORS FOR LOW EMISSIONS

There is a conflict among some of the combustor requirements. For example, the modification required to reduce the smoke and nitric oxides (NO and NO_2, termed NO_X) will increase the emissions from carbon monoxide (CO) and unburned hydrocarbon (UHC), and vice-versa. Throttling the airflow to the combustor can solve this problem. A device having a variable cross-sectional area is used to control the flow. Large quantities of air are admitted at high pressures, resulting in minimized formation of soot and nitric oxide. At low pressures, the cross-sectional area is reduced, leading to an increase in the fuel-to-air ratio and a reduction in the velocity of the flow. This change improves the ignition characteristics and increases the combustion efficiency, resulting in a reduction in the CO and UHC emissions. This technique of variable cross-sectional areas has been used on a few large industrial gas turbines. Its main disadvantage is the requirement of complex control systems that result in increasing the weight and cost and reducing reliability. This method has been ruled out for small gas turbines and aeronautical applications.

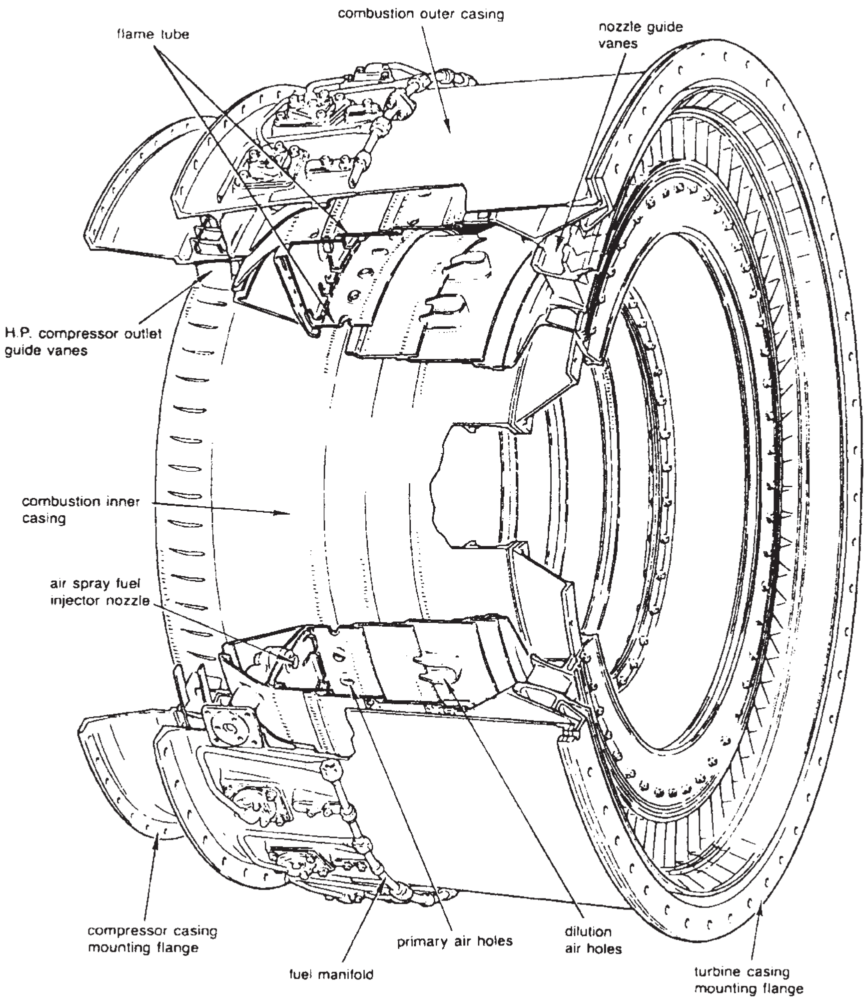

FIGURE 12.12 Aircraft-type annular combustion chamber. (© *Rolls-Royce Limited.*)

Staged combustion is an alternative solution for achieving all of the requirements of modern combustors. The staging could be *axial* or *radial.* In both cases, two separate zones are used. Each zone is designed specifically to improve certain features of the combustion process. Figure 12.13 illustrates the principle of axial staging. The primary zone (zone 1) is lightly loaded. It operates at a high equivalence ratio ϕ of around 0.8 ($\phi = 0.8$ indicates that the amount of air available is slightly more than needed for combustion). This is done to improve the combustion efficiency and minimize the production of CO and UHC. Zone 1 provides all of the power requirements up to operating speed. It acts as a pilot source of heat for zone 2 at higher power levels. Zone 2 is the main combustion zone. The air and fuel are premixed before entering zone 2. The equivalence ratio in both zones is maintained around 0.6 at full power. This is done to minimize the NO_X and smoke emissions.

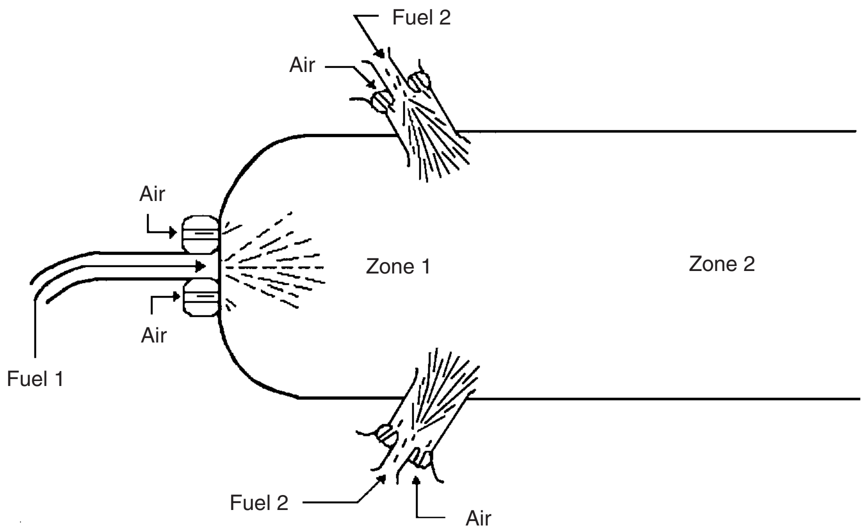

FIGURE 12.13 Principle of axial staging. Low power: $\phi_1 = 0.8$; $\phi_2 = 0.0$. High power: $\phi_1 = 0.6$; $\phi_2 = 0.6$.

Most modern gas turbines use staged combustion when burning gaseous fuels. This method is used to reduce the emission of pollutants without requiring steam or water injection. Some gas turbines use a *lean premix prevaporize* (LPP) *combustor* for liquid fuels. This technique seems to be the most promising for generating an ultralow level of NO_X. Figure 12.14 illustrates this concept. The objectives include:

- To evaporate all the fuel
- To mix the fuel and air thoroughly before combustion

The emissions of nitric oxide are drastically reduced for the following reasons:

- This technique avoids the burning of liquid droplets, resulting in a reduction in the flame temperature and elimination of the hot spots from the combustion zone (i.e., the concentration of nitric oxide drops with temperature).
- The combustion has a lean fuel-to-air ratio.

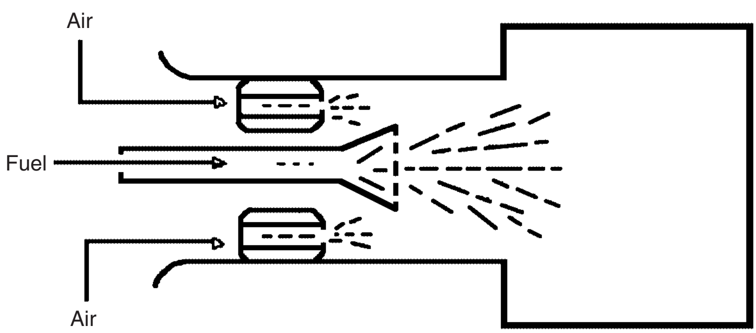

FIGURE 12.14 LPP.

The main disadvantage of the LPP system is the possibility of autoignition or flashback in the fuel preparation duct. This phenomenon could occur at the high pressures and inlet temperatures reached during full-power operation. It is caused by the long time needed to fully vaporize and mix the fuel at low power conditions. These problems can be solved by using staged combustors and/or variable cross-sectional areas to throttle the inlet air. Other concerns with the LPP systems are in the areas of durability, maintainability, and safety.

The *rich-burn/quick-quench/lean-burn* (RQL) *combustor* is another alternative for achieving ultralow NO_X emissions. This design has a fuel-rich primary zone. The NO_X formation rate in this zone is low due to the low temperature combustion and oxygen depletion. Additional air is injected downstream of the primary zone. It is mixed rapidly with the efflux from the primary zone. If the mixing process were slow, pockets of hot gas would last for a sufficient period to generate significant amounts of NO_X. Thus, the effectiveness of the quick-quench mixing section is essential for the success of the RQL combustors.

The catalytic combustor appears to be the most promising device for low NO_X emissions. It involves prevaporizing the fuel and premixing it with air at a very low equivalence ratio (i.e., the amount of air is much more than needed to participate in combustion). The homogeneous mixture of air and fuel is then passed through a catalytic reactor bed. The catalyst allows the combustion to occur at a very low concentration of fuel. The concentration of fuel is lower than the lean flammability limit. Thus, the reaction temperature is extremely low. Therefore, the resulting NO_X concentration is minimal. Most modern gas turbines have a thermal reaction zone downstream of the catalytic bed. The functions of the thermal reaction zone are as follows:

- To increase the gas temperature (the thermal efficiency increases with temperature)
- To reduce the concentration of CO and UHC

The capability of catalytic reactors for producing a very low emission level of pollutants has been known for more than 30 years. However, the harsh environment in combustors limited the development of this option in gas turbines. The durability and lifetime of the catalyst were always a problem. Considerable research is underway on catalysts. However, it is unlikely that it will be applied to aero engines in the near future. Considerable experience on stationary gas turbines is required before implementing this feature in aero engines. It is expected that it will be in the form of a radially staged, dual-annular combustor (Fig. 12.15) when it will be implemented. The outer combustor is used for easy ignition and low emissions when the engine is idling. At higher power levels, the mixture of air and fuel is supplied to the inner combustor. The catalytic reactor is embedded inside the inner combustor. This is the reactor that provides most of the temperature increase during full-load operation.

COMBUSTORS FOR SMALL ENGINES (LESS THAN 3 MW)

High shaft speeds of small gas turbines require close coupling of the compressor and turbine. This is necessary to reduce the problems with shaft whirling. This requirement has led to the development of annular reverse-flow or annular radial-axial combustors. This design is used almost universally in small engines. The Allison T63 engine is an exception. It has a single tubular combustor installed at the end of the engine to facilitate inspection and maintenance. Figure 12.16 illustrates an annular reverse-flow combustor. The main advantages are as follows:

- The combustion volume is used efficiently.
- The fuel injectors are accessible.

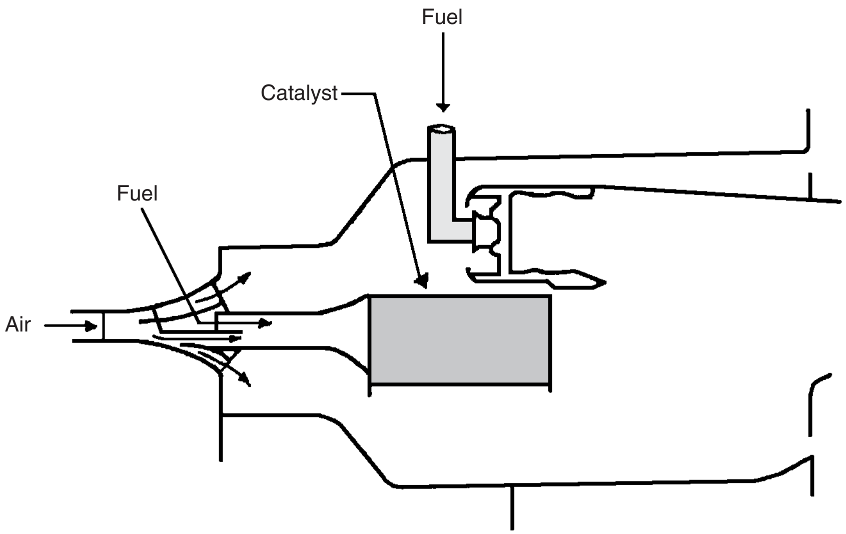

FIGURE 12.15 Combination of catalytic and conventional staged combustors.

These advantages are in addition to the significant reduction in shaft length. Small combustors have problems in ignition, wall cooling, and fuel injection. The size and weight of the ignition equipment is relatively large. However, they cannot be reduced, because this will lead to a reduction in reliability. Difficulties have been experienced in providing adequate cooling for the liner wall of small annular combustors. These stem from the relatively large surface area that must be cooled. The problem is compounded by the low velocities in the annulus. These are associated with centrifugal compressors (small gas turbines use centrifugal rather than axial-flow compressors because small axial-flow compressors drop in efficiency, but centrifugal compressors maintain their efficiency for small sizes). This results in poor convective cooling of the external surface of the liner. Angled effusion cooling appears to be the most suited for this application.

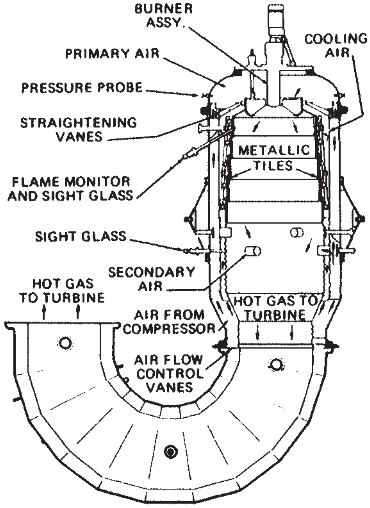

FIGURE 12.16 A typical single-can side reverse-flow combustor for an industrial turbine. (*Courtesy Brown Boveri Turbomachinery, Inc.*)

The fuel injection methods for small, straight-through annular chambers have not been completely satisfactory yet. The problem is caused by the need to use a large number of fuel injectors. This is necessary to meet the requirements of high combustion efficiency, low emissions, and good pattern factor. However, the size of the fuel injector decreases as the number of injectors increases. Industrial experience proved that small passages and orifices (<0.5 mm) are prone to erosion and blockage. Thus, the minimum size of the atomizer is limited.

Solar developed an airblast atomizer for their small annular combustors. The atomizer is installed on the outer liner wall. It injects fuel tangentially across the combustion zone. A small number of injectors is needed for each combustor. This design is known for providing good atomization even at start-up. The trend in the development of gas turbines is for higher pressure in the combustors and turbine inlet temperature. Research is underway in the areas of wall cooling, fuel preparation and distribution, miniaturized ignition devices, and high-temperature materials including ceramics. This will address the special requirements of small annular combustors.

INDUSTRIAL CHAMBERS

The most important criteria for industrial engines are reliable and economical operation for long periods of time without requiring attention. Compactness is not a consideration in this case. Thus, these engines must provide fuel economy, low pollutant emissions, and capital cost. Ease of maintenance and maximization of capacity factor (percent of time the unit is operating at full power) will play a major role in determining the market share of a specific engine.

To meet these objectives, industrial engine combustors are normally larger than the ones in aeronautical engines. Thus, the residence time inside the combustors is longer. This is an advantage when the fuel quality is poor. Also, the pressure drop across the combustors is smaller due to a lower velocity of the flow. The two categories of industrial engines are the following:

1. *Heavyframe machines.* They are designed to burn gaseous fuels, heavy distillates, and residual oils. They do not follow aeronautical practice.
2. *Industrialized aero engines.* They normally burn gaseous and/or light to medium distillate fuels. They follow aircraft practice closely.

The GE MS-7001, 80-MW gas turbines are one of the most successful industrial engines. There are 10 sets of combustion hardware in each machine. Each set includes a casing, an end cover, a set of fuel nozzles, a flow sleeve, a combustion liner, and a transition piece, as shown in Fig. 12.17. The flow sleeve has a cylindrical shape. It surrounds the liner and aids in distributing the air uniformly to all liners. Each combustor has one fuel nozzle in the conventional MS-7001. Multiple fuel nozzles are used for each combustor in the more advanced DLE versions. Some industrial engines have a single large combustor. It is installed outside the engine, as illustrated in Fig. 12.18. This design allows the combustor to meet the requirements of good combustion performance. The outer casing of the unit can be designed to withstand the high pressure. This arrangement has another advantage. It is the ease of inspection, maintenance, and repair. They can all be performed without removing the large components in the casing. The two types of liners are as follows:

1. *An all-metal liner having fins.* It is cooled by a combination of convection and film cooling.
2. *A tube of nonalloy carbon steel.* It has a refractory brick lining. This design requires less cooling air than the all-metal type.

It is preferable to use multiple fuel injectors (burners) for these combustors for the following two reasons:

1. They provide a shorter flame
2. The gases flowing into the dilution zone will have a more uniform temperature distribution.

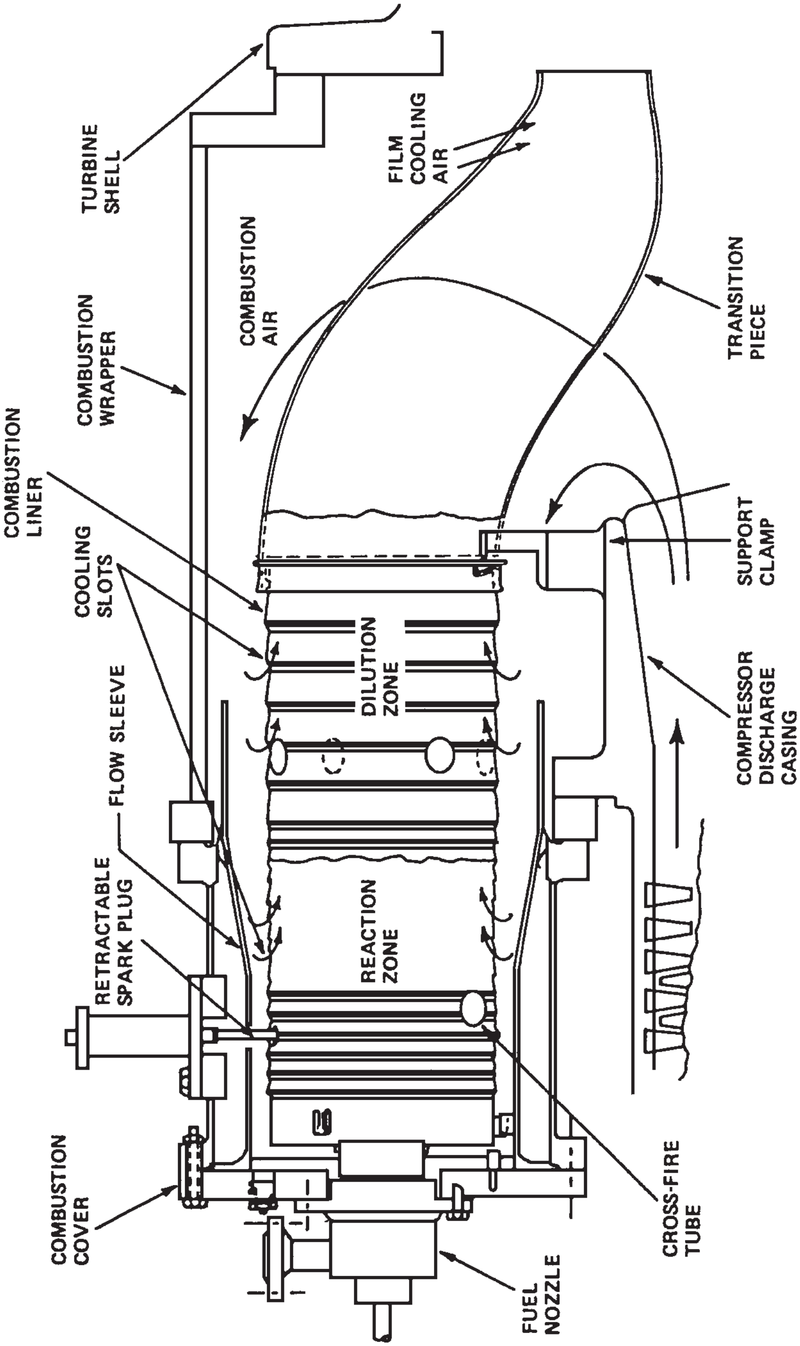

FIGURE 12.17 MS7001 combustion system. (*Courtesy of General Electric Company.*)

A number of "hybrid" burners are installed on the Siemens Silo combustors. They burn natural gas in either diffusion or premix modes. They emit a low level of pollutants over a wide range of loads. At low loads, the system operates as a diffusion burner. At high loads, it operates as a premix burner. Siemens used the same fuel burner in their silo-type combustors for engines having different power ratings. They only changed the number of burners to accommodate the changes in the size of the engine. However, the number of burners in their new annular combustors was fixed at 24. This was done to provide good pattern factor. The main disadvantage of this design is that the size of the burners must vary with the rating of the machine. However, the basic design remained the same. The Siemens hybrid burner has been proven to provide low emissions for engines in the 150-MW rating. This design has also been used by MAN GHH to its THM-1304 engine, which is a 9-MW gas turbine. It has two tubular combustion chambers. They are mounted on top of the casing.

ABB has developed a conical premix burner called the *EV burner.* It burns gas and liquid fuels satisfactorily and has been proven to provide low NO_X emissions in different applications. The ABB GT11N gas turbine has a silo combustor. It has 37 of these burners. They all operate in a premix mode. Fuel is supplied to some of these burners only during part-load operation. The annular combustors use the same technology. The ABB GT10 (23 MW) combustor has 18 EV burners in a single row. The ABB GT13E2 is a heavy-duty gas turbine (>150 MW). It has 72 EV burners. They are arranged in two staggered circumferential rows.

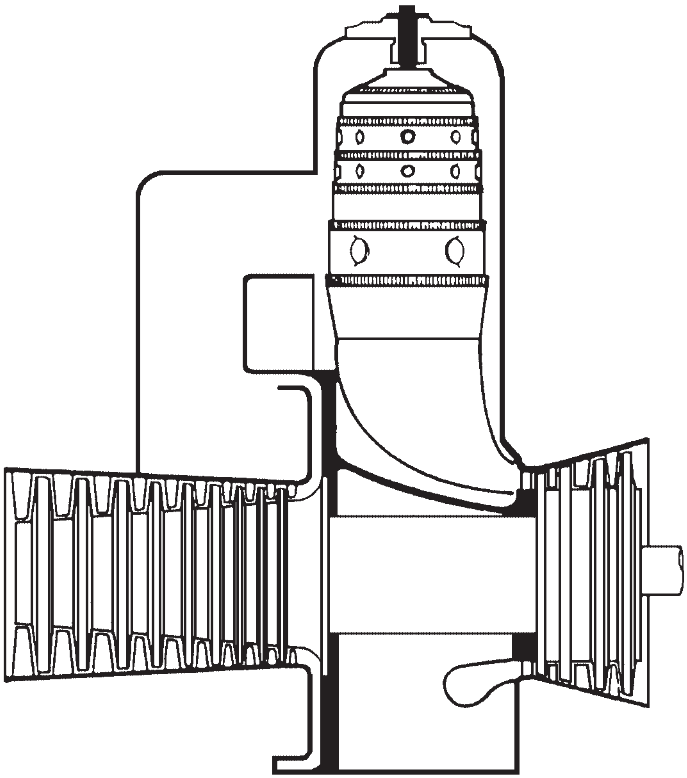

FIGURE 12.18 Industrial engine featuring single tubular combustor.

AERODERIVATIVE ENGINES

The modifications of aero engines to suit industrial and marine applications have been used for more than 30 years. For example, the Allison 501 engine is basically their T56 aero engine. It has been modified to burn DF2 fuel instead of kerosene (aviation fuel). The initial design of this engine had six tubular (can) combustors. However, the modern 501-K series of engines has a can-annular configuration. It has six tubular cans. They are located within an annular casing. The combustor version for dry low emission (DLE) burns natural gas using a dual-mode technique. It meets its emission goals without using water or steam injection. Many other companies used the same method to convert aero engines to industrial and transport applications. For example, Rolls-Royce developed industrial versions of their Avon, Tyne, and Spey aero engines. The fuel injectors were changed sometimes to handle multi-fuels. They were also modified to allow the injection of water or steam to reduce NO_X. The primary-zone pattern of airflow was modified to add more air. This was done for two reasons:

1. To take advantage of the absence of the requirement to relight at high altitude
2. To reduce the formation of soot and smoke

These simple modifications to an aero combustor will not be adequate in the future, mainly because emission regulations are becoming stricter. More sophisticated techniques will be required. Modern industrial DLE combustors achieve their emissions targets by using fuel staging and fuel-air premixing. The aero GE LM-6000 and RR-211 DLE industrial engines both use staged-combustion gaseous mixtures of fuel and air. These two engines were derived from successful high-performance aero engines. Their existing aero combustors were replaced by DLE combustors having the same length. Figure 12.19 illustrates the RB-211. The Trent is one of the most recent aero industrial engines manufactured by Rolls-Royce (Fig. 12.20). It uses three separate stages of premixed fuel-air injection.

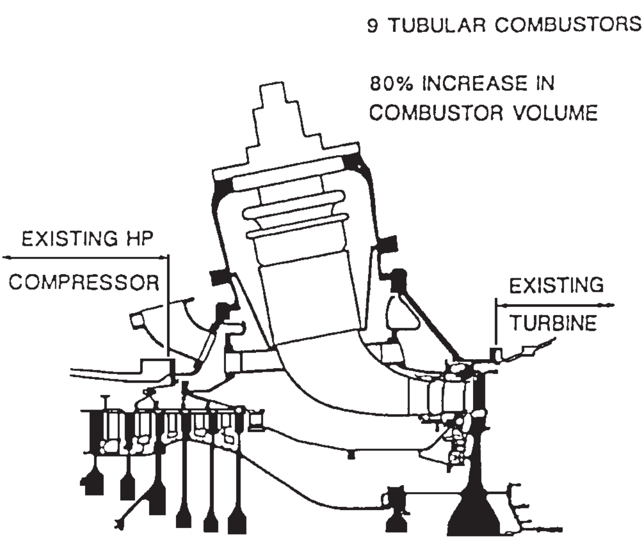

FIGURE 12.19 Industrial RB-211 DLE combustor. (*Courtesy of Rolls-Royce Limited.*)

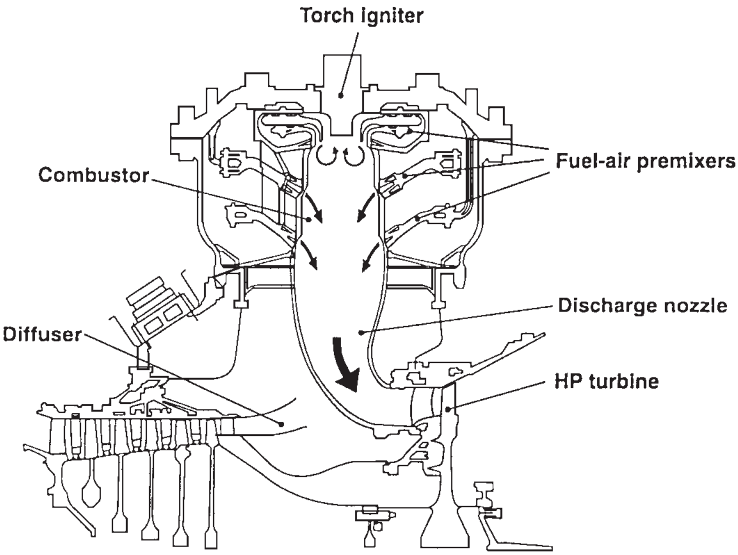

FIGURE 12.20 Industrial Trent DLE combustor. (*Courtesy of Rolls-Royce Limited.*)

REFERENCE

Boyce, M. P., *Gas Turbine Engineering Handbook,* Gulf Publishing Company, Houston, Tex., ©1982, reprinted July 1995.